The Apollo $\gamma$-ray array for HELIOS

Experiment development:

Nuclear reaction and mass models:
T. Kawano, P. Talou and P. Möller (T2)

Supernova modeling:
C. Fryer, A. Hungerford, and G. Rockefeller (CCS, XTD)

*ATLAS Users Meeting on May 15-16 2014*
Addition of gamma detection for transfer reactions expands physics output

Prediction of neutron capture rates can be improved by studying
Level densities
γ-ray decay schemes
γ-ray multiplicities
Photon strength function

Design goals:
1. highest detection efficiency with segmentation
2. Operate inside HELIOS – 3 T magnetic field and vacuum
3. portable
Segmented $\gamma$-ray detector array

**Ideal:**
tapered 20 hexagons and 6 pentagons as a closely-packed geometry

**Realistic solid angle coverage:**
1. 26-cylinder geometry covering about one $\pi$
2. 2 inch in diameter and 3 inch long
3. 15 CsI(Tl) scintillators and 6 LaBr$_3$(Ce) scintillators
4. Customized light readout was required
Light readout under magnetic field

**Sensl-silicon photomultiplier (SPM)**

1. 36 X 36 mm² pixelated avalanche photodiodes
2. Used the wavelength shift paint for BrilLanCe380 ($\lambda = 380$ nm), since quantum efficiency (QE) peaks at $\lambda = 550$ nm, optimized for CsI(Tl)
3. SPM + power supply + preamplifier was provided by Sensl
Apollo array: measured energy resolution and efficiency

Above 1 MeV, the resolution is less than 4%

Measured $\gamma$-ray energy spectrum of $^{133}$Ba source shows a good separation of 50 keV at 300 keV

Apollo peak efficiency is measured to be about 15% at 1 MeV
Apollo is implemented inside HELIOS

Successful commissioning experiment of the APOLLO array in Jan. 2013 for performing in vacuum and under the magnetic field with γ-ray sources
First beam test at ANL: $d(^{17}\text{O},p\gamma)^{18}\text{O}$

Proton groups detected by Position Sensitive Silicon array in HELIOS

$\gamma$-ray decay transitions observed by APOLLO in coincidence with the excited states of $^{18}\text{O}$.

Proton Lab Energy (MeV)

Distance from the target (arb. Unit)

$^{22}\text{Na}$ source decay

Energy (keV)
Further improvements can be done

**Energy resolution**
1. Sensl has developed the shorter wavelenth SPM ($\lambda_{\text{peak}} = 420$ nm)
2. Shorter shaping time or baseline restoration using digital filters.
3. Replace CsI(Tl) with LaBr$_3$(Ce)

**Efficiency**
Closely packed geometry

**Flexibility**
1. Implementation with digital electronics
2. Coupled with other instruments
Path Forward

We have developed the APOLLO array to measure $\gamma$-rays in coincidence with transfer reactions for exploring the nuclear properties off the stability.

Currently the stable $^{136}$Xe beam time has been scheduled in June 2014 in order to test the system with heavy beams. Upon the success of this, planning to expand to unstable isotopes.
Extras
Details

- **Timing** -- Sensl is sensitive to this issue
  - Best results have been achieved using digital filters
- **Total cost**:
  - $150 k for Sensl for 30 modules, including R&D
  - Now $2k for only SPM
  - LaBr3(Ce) - $13k for 2X2 LaBr3 $17k for 2X3
Digital signal processing: digital filter

- $^{22}$Na calibration source was used.
- After the peaks are detected, the waveform is integrated over 5 $\mu$s.
How to tie this $\gamma$-ray data with Monte-Carlo Hauser-Feshbach calculation?

We have demonstrated how to deduce nuclear properties using Monte-Carlo Hauser-Feshbach code (MCHF) with DANCE data at LANSCE

$^{43}$Ca$(n,\gamma)$ measurement at LANSCE: $E_R = 5.18$keV (3$^-$)

RED : DANCE data,   BLUE : MCHF + GEANT4 simulation
How to tie this $\gamma$-ray data with Monte-Carlo Hauser-Feshbach calculation?

Nuclear properties are deduced using Monte-Carlo Hauser-Feshbach code (MCHF) with DANCE $^{238}$U(n,$\gamma$) data at LANSCE

2-step $\gamma$-ray cascade shows better fit with M1 strength

Better nuclear input feeds

Calculated MCHF cross section is improved

Ullmann et al. 
PRC (2014)